



Article

Enhancing High-Temperature Oxidation Stability of Recycled Carbon Fibers Through Ceramic Coating

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Abstract

Carbon fiber-reinforced composites (CFRCs) have attracted considerable attention in recent years due to their excellent properties, enabling their use across various sectors. However, their application at high temperatures is limited by the fibers' lack of oxidation resistance. This study demonstrates a significant advancement in enhancing the oxidation stability performance of carbon fiber-reinforced composites (CFRCs) by developing a silicon carbide (SiC) coating through the ceramization of carbon fibers using silicon (Si) powder. For the first time, this method was applied to recycled carbon fibers from CF thermoplastic composites. The key findings include the successful formation of a uniform SiC coating, with coating thickness increasing with process duration and decreasing at higher temperatures. The treated fibers exhibited substantially improved oxidation resistance, maintaining structural stability above 700 °C—markedly better than that of their uncoated counterparts. Thermogravimetric analysis confirmed that oxidation resistance varied depending on the CF/Si ratio, highlighting this parameter's critical role. Overall, this study offers a viable pathway to enhance the thermal durability of recycled carbon fibers for high-temperature applications.

Keywords: carbon fibers; ceramization; chemical vapor reaction; oxidation resistance



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1. Introduction

The use of new materials like fiber-reinforced plastic and/or ceramic composites has undisputed advantages, including enhanced properties such as mechanical strength, thermal resistance, electrical conductivity, lightness and lower energy consumption during use. Initially developed for military purposes, these materials, most notably those based on glass and carbon, later found applications in cutting-edge sectors like aerospace, shipbuilding, energy, automotives and construction. In addition, their excellent performance has driven the steady expansion of uses over time, from high-level applications to a wide range of everyday tools and products [1–3].

Carbon fibers (CFs) are inorganic fibers with outstanding mechanical (high stiffness, remarkable tensile strength, high strength-to-weight ratio) and chemical–physical (excellent chemical resistance, high temperature tolerance and low thermal expansion) properties all while being incredibly lightweight. They exhibit properties comparable to steel yet

maintain a weight like that of plastics. Due to their high cost as compared to other types of reinforcing fibers, such as glass, basalt or plastic fibers [4], CFs are predominantly employed in high-quality products. They are largely exploited as reinforcing agents in polymeric composites, where the binding polymer can either be a thermoset resin (e.g., epoxy) or a thermoplastic polymer (e.g., polyester, vinyl ester or nylon). The overall characteristics of the resultant composite, the carbon fiber-reinforced composite (CFRC), significantly depend on the choice of polymer and additives introduced into the binding matrix [5].

The widespread use of CFRCs has led to the generation of increasing quantities of CF waste. A remarkable total production of 62,000 tons of CF waste was attained in 2020, and if no measures are taken, the global CF waste yield from the aircraft sector and the wind turbine industry is estimated to reach nearly 500,000 tons by 2035. The management of end-of-life products (EOLPs) is crucial for fostering a sustainable industry aligned with the principles of the circular economy. The establishment of effective recycling pathways should be motivated by both economic and environmental factors [6,7]; thus, recycling processes for CFRCs waste must be designed to recover fibers that can subsequently be repurposed in the production of new composites [8–10]. Recycling serves as an effective strategy to reduce environmental impact while addressing the increasing demand for this material across multiple industrial sectors, such as aerospace, wind blades, sports leisure, pressure vessels, automobiles and construction [11,12].

Another peculiar aspect related to carbon fibers is that they are not sufficiently stable in the presence of oxygen. This susceptibility to oxidation restricts their use in composites, as they tend to react with oxygen and degrade rapidly above 500 °C [13]. Additionally, when carbon fibers interact with most metallic and ceramic matrix materials, the mechanical properties of the resulting composites are compromised. These drawbacks could be overcome by protecting carbon fibers with a ceramic coating [14–16], which, acting as a barrier, can improve the oxidation resistance, mechanical strength and chemical stability of the fibers. This makes them suitable for high-performance applications such as aerospace, automotives and other environments involving high temperatures. Among the different ceramic matrixes, silicon carbide (SiC) is one of the most promising materials for protective coatings, thanks to its remarkable oxidation resistance and mechanical properties [17].

The most common techniques used in preparing SiC films include the precursor infiltration of carbon fibers [18–20] (typically with a liquid or polymer-containing silicon) and high-temperature treatment (generally between 1000 °C and 1800 °C) in an inert or reactive atmosphere. During this heat treatment, the silicon-based precursor undergoes chemical reactions, forming a silicon carbide (SiC) matrix and gradually converting the carbon fibers into ceramic fiber. However, precursor-based methods involve additional processing steps, such as precursor impregnation and pyrolysis, which complicate and extend the ceramization process. Furthermore, some silicon precursors, including polysilazanes, can be expensive.

Chemical vapor deposition (CVD) is another widely used method for the synthesis of dense and homogenous SiC coatings with various shapes [21–23]. At the same time, this process requires the use of expensive precursors and specialized equipment, which strongly limits its utilization. Furthermore, the low deposition rate and time-consuming process make the CVD method less practical and cost-efficient in many cases.

The carbothermal reduction technique [24,25] presents an alternative approach, involving the preparation of a SiO₂-based coating on carbon fibers, followed by the reduction of SiO₂ to SiC at high temperatures. This method is generally compatible with carbon fibers, making it simple and easy to conduct. Nonetheless, there are some notable drawbacks. The initial SiO₂-based coating is typically prepared using a sol-gel process, which requires costly and non-environmentally friendly precursors and solvents. Furthermore, the reac-

tion to reduce SiO₂ to SiC demands high temperatures (1400–1650 °C), during which some carbon (C) from fibers is converted into CO/CO₂. This, apart from causing carbon loss, can also damage the structure of carbon fibers, adversely affecting their properties.

Recently, the Chemical Vapor Reaction (CVR) has emerged as a promising method for reducing the costs associated with producing SiC coatings [26–28]. This method relies on the direct reaction of the carbon matrix and silicon vapor, producing SiC coatings in a straightforward and cost-effective manner.

Although the CVR method has proven to be a promising method for producing silicon carbide (SiC) coatings, most studies have focused on its application to virgin materials, largely overlooking the potential of post-consumer recycled carbon fibers. This represents a notable gap in advancing both sustainable material practices and the broader utilization of CVR technology in coating processes. The novelty of this study lies in extending the CVR method to fabricate SiC coatings on recycled carbon fibers by a direct reaction with silicon powders. The recycled fibers, which typically exhibit diminished properties compared to their virgin counterparts, pose challenges in terms of coating adhesion and thermal stability. In this work, a series of experimental tests was conducted using a CVR process to produce silicon carbide coatings on recycled carbon fibers, with the aim of enhancing their stability at high temperatures while adding value to post-consumer CFs. The influence of the reaction temperature, duration and silicon quantity on the morphology and microstructure of SiC-coated carbon fibers was analyzed. In addition, the oxidation behavior for the synthesis of the SiC coating was investigated and discussed. By tailoring the CVR process specifically for recycled fibers, this work introduces a novel approach to improving their oxidation stability performance.

2. Materials and Methods

Carbon fibers (rCFs) were recovered from PPS/CF (Cetex TC1100, Tencate Advanced Composites, Nijverdal, The Netherlands) composite waste materials obtained from the post-processing of sheet lamination-based additive manufacturing products, kindly supplied by Aerosoft S.p.A (Capua, Italy). The data sheets indicate a resin content close to 34%wt.

Recovery tests were conducted on approximately 5 g of sample per recovery cycle in a tubular Lenton furnace (LTF 12/100/610 model) using the patented carbon fiber recovery process developed by ENEA [29].

The recovered rCFs (see SEM pictures in Figure 1) exhibit a length ranging from 5 to 400 μm, a diameter of 7 μm and a density of 1.75 g/cm³. The density of the carbon fibers was measured in accordance with the ISO standardized method. This measured value was then compared to the specifications provided in the data sheet of the original material (PPS/CF, Cetex TC1100, Toray Advanced Composites, Nijverdal, The Netherlands). As stated in the patent related to the recovery process [29], rCFs maintain 90% of their mechanical properties, specifically in terms of tensile strength and Young's modulus, when compared to virgin CFs.

Silicon powder of PV grade, with a particle size range of 0–40 microns, provided by Titolchimica SpA (Villamarzana (RO), Italy), was used for the ceramization trials.

The process conditions of the ceramization tests are summarized in Table 1. The coating of the recycled fibers (rCFs) was achieved via a silicon-based reaction carried out under varying process conditions, as detailed in tests 1–8 in Table 1, with a systematic variation in the rCF:Si ratio, reaction time and temperature. The mixed reagents were placed in an Alsint boat and processed in a high-temperature tube furnace (Nabertherm RHTH 120/300/18, Nabertherm GmbH, Lilienthal, Germany). The reactions were conducted under an argon atmosphere, at a gas flow rate of 1 l/min.

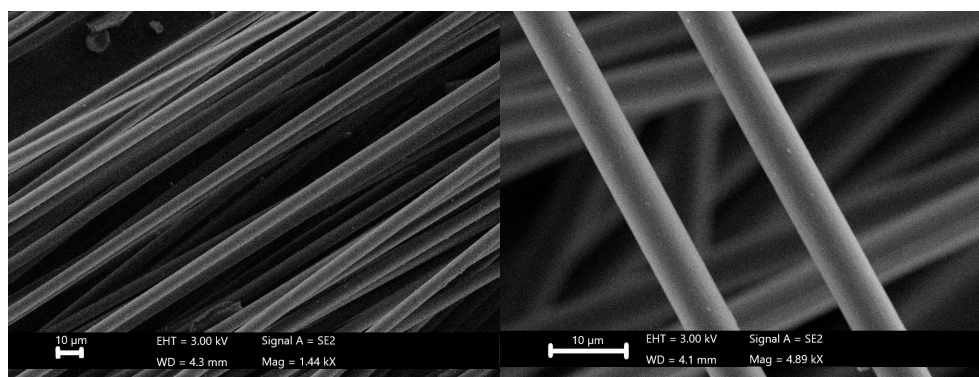


Figure 1. SEM images of rCFs at different magnifications.

Table 1. Parameters of ceramization tests in argon atmosphere (1 slm).

Test Code	Temperature (°C)	Time (min)	Reagent Ratio
1	1650	90	rCF:Si = 1:1
2	1650	90	rCF:Si = 1:0.5
3	1650	90	rCF:Si = 1:0.25
4	1650	90	rCF:Si = 1:0.05
5	1650	150	rCF:Si = 1:0.25
6	1650	180	rCF:Si = 1:0.25
7	1500	90	rCF:Si = 1:0.25
8	1450	90	rCF:Si = 1:0.25

The crystallinity and structural phases of the powders were analyzed using X-ray diffraction (XRD), through an X'Pert MPD (Malvern Panalytical, Almelo, The Netherlands) diffractometer using nickel-filtered Cu K α radiation in the range of $2\theta = 20\text{--}80^\circ$, with a step width of 0.050° and a counting time of 5 seconds per step. The data were collected by comparing the diffraction patterns of the samples with SiC Joint Committee on Powder Diffraction Standards (JCPDS) card No. 29-1129.

Morphological analyses of the samples were carried out using a scanning electron microscope (SEM, “Phenom Pure” with upgrade to Phenom ProX, Thermo Fisher Scientific, Waltham, MA, USA), which was also used for the determination of diameter and coating thickness. These parameters were evaluated as the average of 10 measurements taken at different positions on each sample.

Thermogravimetric analyses were performed using a simultaneous Thermal Analyzer—STA 449 F3 Jupiter[®] (Netzsch-Gerätebau GmbH, Selb, Germany) to investigate the oxidation behavior of the ceramic-coated fibers. The experiments took place in an air atmosphere with a flow rate of 50 mL/min, at a heating rate of $10^\circ\text{C}/\text{min}$ over a temperature range of $30\text{--}1000^\circ\text{C}$.

3. Results

3.1. Structural and Morphological Analyses of Samples Obtained at Different rCF:Si Molar Ratios

The XRD diffractograms of ceramic-coated rCFs are shown in Figure 2. These results correspond to products synthesized at different rCF:Si molar ratios while maintaining a constant process temperature of 1650°C and a residence time of 90 min (tests 1–4).

All the diffractograms highlight the crystalline nature of the coating, displaying the main peaks of the silicon carbide structure in its β form at 2θ values of approximately 35.8 , 41.3 , 60.0 , 72.0 and 75.4° corresponding to the (111), (200), (220), (311) and (222) crystal planes, respectively. Low-intensity signals of α -SiC are slightly visible at 34.1° and 38.1° . The broad peak at 25.5° is attributed to carbon fibers. In the diffractograms of tests 1 and 2,

non-reacted silicon is still visible at about 28° , while it disappears in test 3. At the lowest Si molar concentration (test 4, rCF:Si = 1:0.05), the ratio between the carbon peak and the SiC signals is higher than that in the other tests.

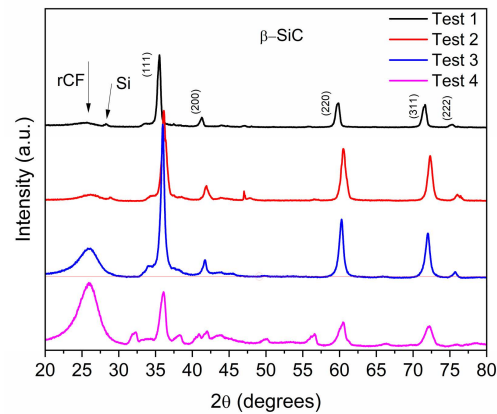


Figure 2. XRD diffractograms of rCFs treated at same process temperature (1650°C) and residence time (90 min) and different rCF:Si molar ratios: rCF:Si = 1:1 (test 1); rCF:Si = 1:0.5 (test 2); rCF:Si = 1:0.25 (test 3); rCF:Si = 1:0.05 (test 4).

Figure 3a–d show the SEM images of the rCFs for tests 1–4.

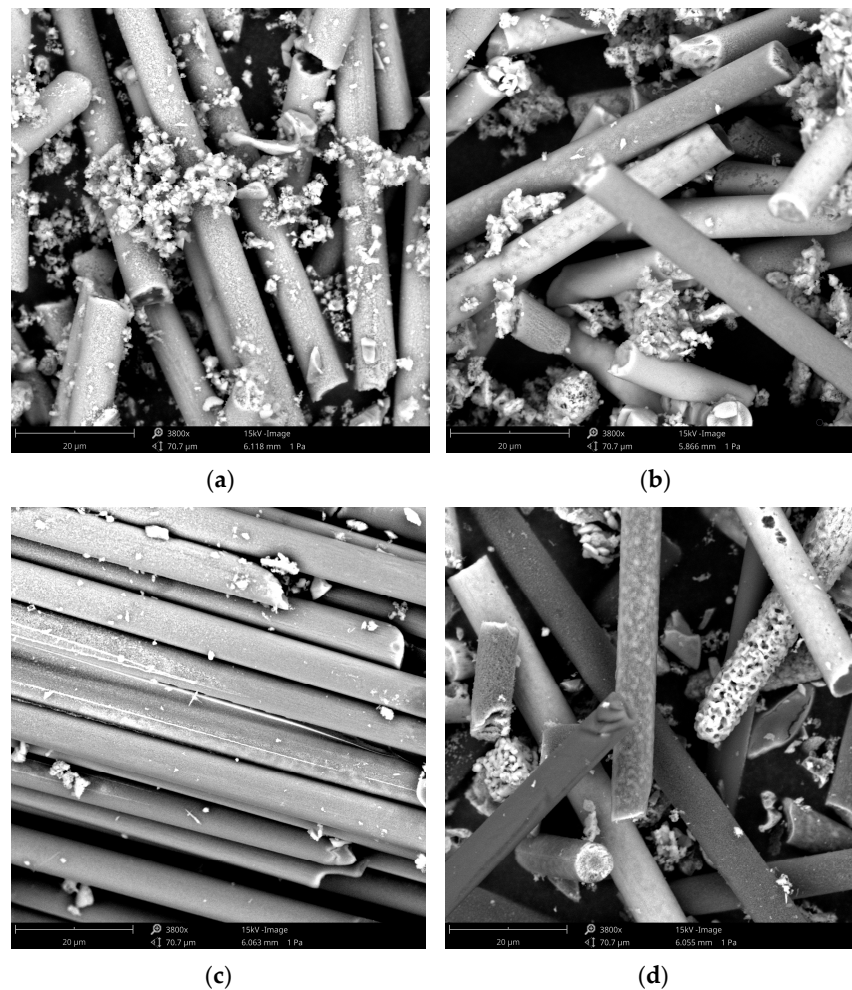


Figure 3. SEM images of rCFs treated at same process temperature (1650°C) and residence time (90 min) and different rCF:Si molar ratios: (a) rCF:Si = 1:1 (test 1); (b) rCF:Si = 1:0.5 (test 2); (c) rCF:Si = 1:0.25 (test 3); (d) rCF:Si = 1:0.05 (test 4).

The images illustrate that in the first three tests (tests 1–3), carbon fibers are entirely enveloped in a ceramic layer (Figure 3a–c), whereas in test 4 the fibers exhibit only a partial coating (Figure 3d). This finding is consistent with the XRD analysis, which indicates that the silicon concentration in test 4 is insufficient to achieve a uniform and continuous coating on the fiber surfaces. Furthermore, SiC crystals can be observed on the surface of the fibers in all samples; additionally, due to the interaction of silicon with microfragments of the fibers, SiC powders are present around the fibers even in test 4, where rCFs are not fully coated.

Both XRD and SEM characterizations suggest that the optimal rCF:Si ratio is 1:0.25 (test 3), where there is no excess of silicon, and the SEM images confirm that the rCFs are completely coated.

As already mentioned, the thickness of the rCF coating was assessed using SEM images (Figure 4). As expected, a decrease in the Si:rCF ratio results in a reduction in coating thickness. The measurements indicate a thickness of 630 nm for test 1, 404 nm for test 2 and 316 nm for test 3. No measurement is available for test 4 due to the non-uniform coating observed on the fibers.

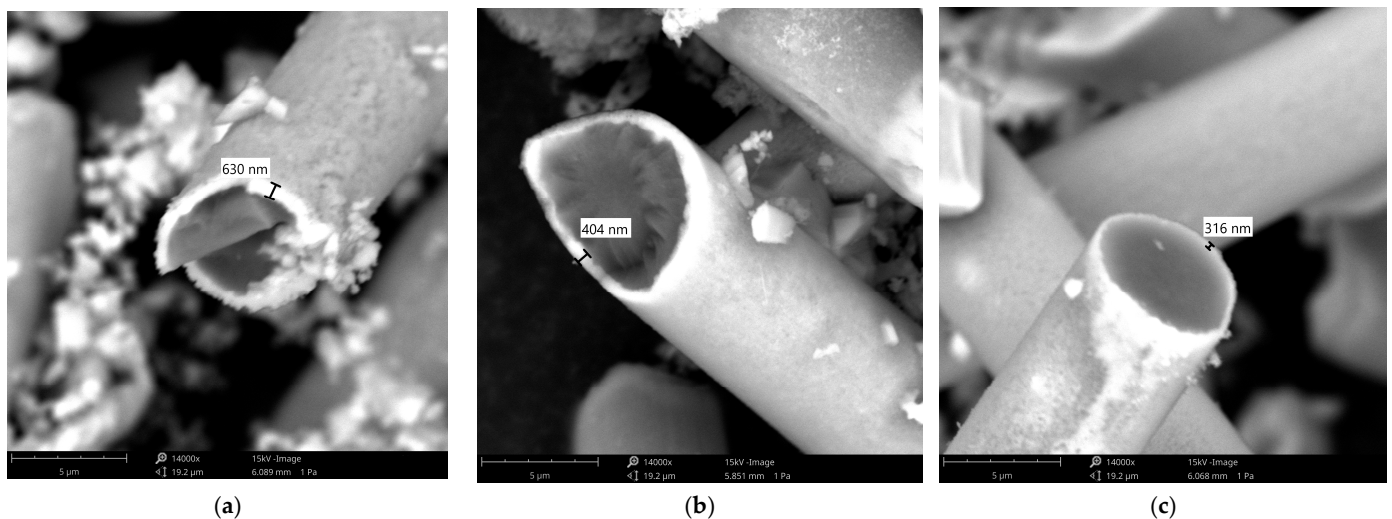


Figure 4. SEM images of rCFs treated at different rCF:Si ratios, same process temperature (1650 °C) and same residence time (90 min): test 1 (a), test 2 (b) and test 3 (c).

3.2. Structural and Morphological Analyses of Samples Obtained at Different Reaction Times

After fixing the molar ratio at rCF: Si = 1:0.25 and setting the reaction temperature at 1650 °C, tests 5 and 6 were performed with varying reaction times of 150 and 180 min, respectively. The outcomes were then compared to those from test 3, which had a reaction time of 90 min.

The XRD diffractograms for tests 3, 5 and 6 were compared (Figure 5), showing no significant differences. Both the rCF and SiC peaks are consistently detected, and their relative intensity ratio remains nearly constant across all three tests.

The SEM images of the rCF/SiC products from tests 3, 5 and 6, shown in Figure 6, reveal a similar surface morphology, characterized by uniformity and the absence of cracks.

In a similar manner, the thickness of the SiC layer exhibits a consistent increase with the extension of the reaction time. Specifically, the thickness increases from roughly 316 nm after 90 min to 400 nm at 150 min and ultimately reaches 689 nm after 180 min.

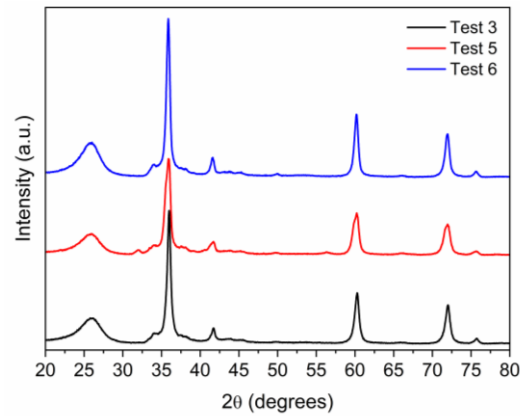


Figure 5. XRD diffractograms of rCFs treated at same process temperature (1650 °C), same rCF:Si ratio (1:0.25) and different residence times: test 3 (90 min), test 5 (150 min) and test 6 (180 min).

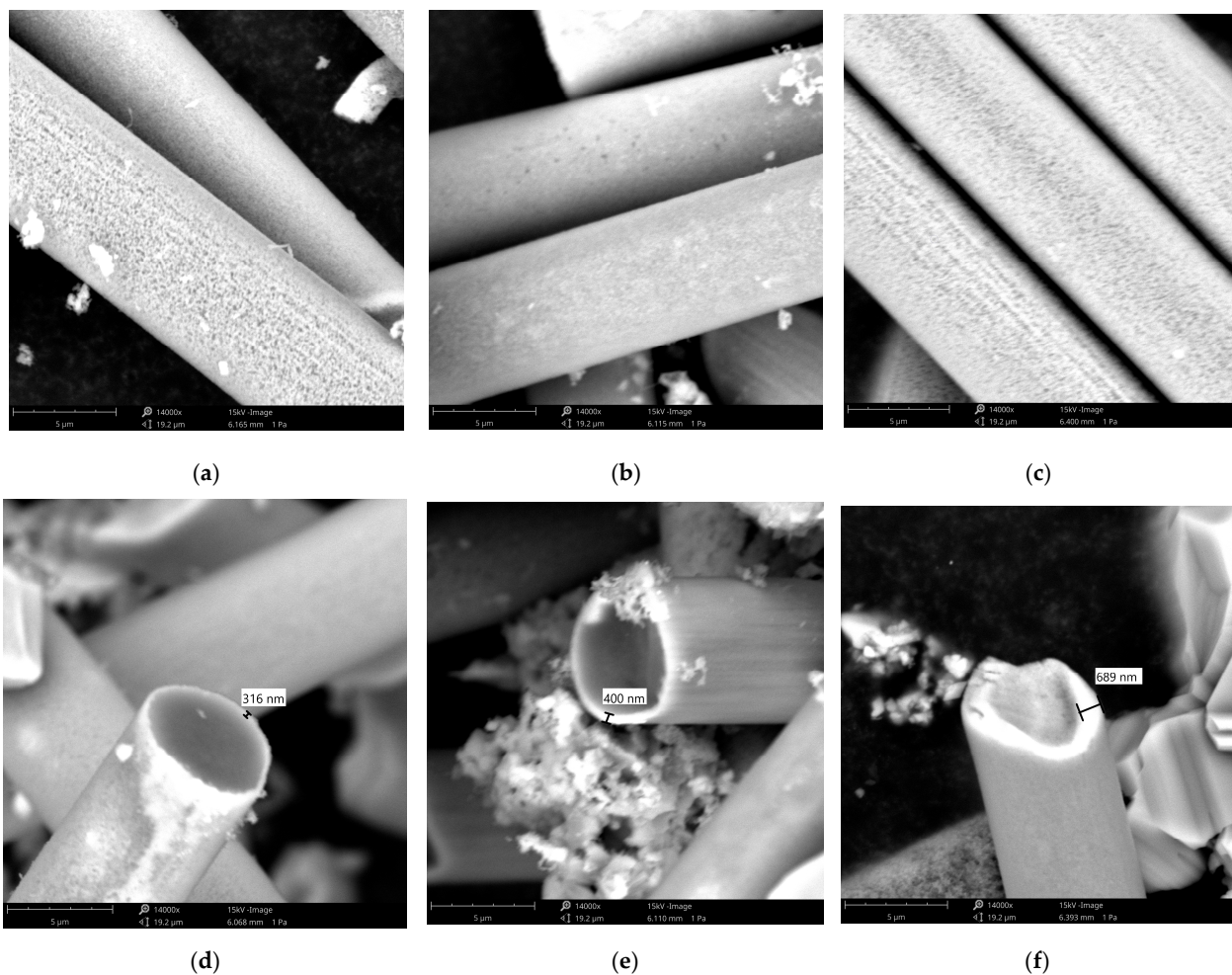


Figure 6. SEM images of rCFs treated at different residence times, same rCF:Si ratio (1:0.25) and same process temperature (1650 °C): test 3 (a,d), test 5 (b,e) and test 6 (c,f).

3.3. Structural and Morphological Analyses of Samples Obtained at Different Temperatures

Tests 7 and 8 were conducted at a constant molar ratio of rCF:Si = 1:0.25 and a reaction time of 90 min, like test 3, but at lower temperatures of 1500 °C and 1450 °C, respectively. These tests aimed to assess the feasibility of the ceramization process at reduced temperatures. The XRD diffractograms shown in Figure 7 reveal SiC peaks for all three tests, with test 8, conducted at 1450 °C, still showing unreacted silicon, as identified by peaks at $2\theta = 28^\circ, 47^\circ$ and 56° .

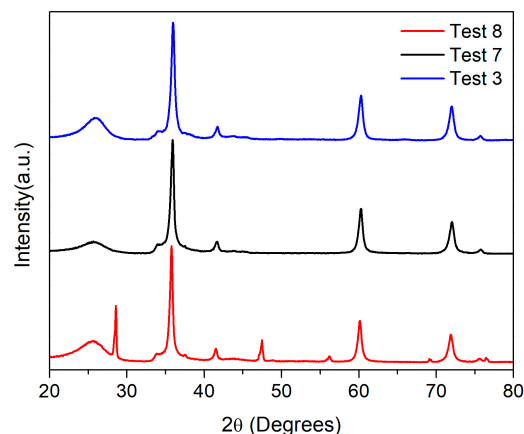


Figure 7. XRD diffractograms of rCFs treated at same rCF:Si ratio (1:0.25), same reaction time (90 min) and different process temperatures: test 3 (1650 °C), test 7 (1500 °C) and test 8 (1450 °C).

Figure 8 compares the SEM images of SiC-coated carbon fibers from tests 8, 7 and 3. The images indicate that there is no variation in SiC thickness as the process temperature increases from 1450 to 1500 °C, with values of 421 nm in test 8 and 424 nm in test 7. However, a reduction in coating thickness is observed in test 3, which was conducted at 1650 °C.

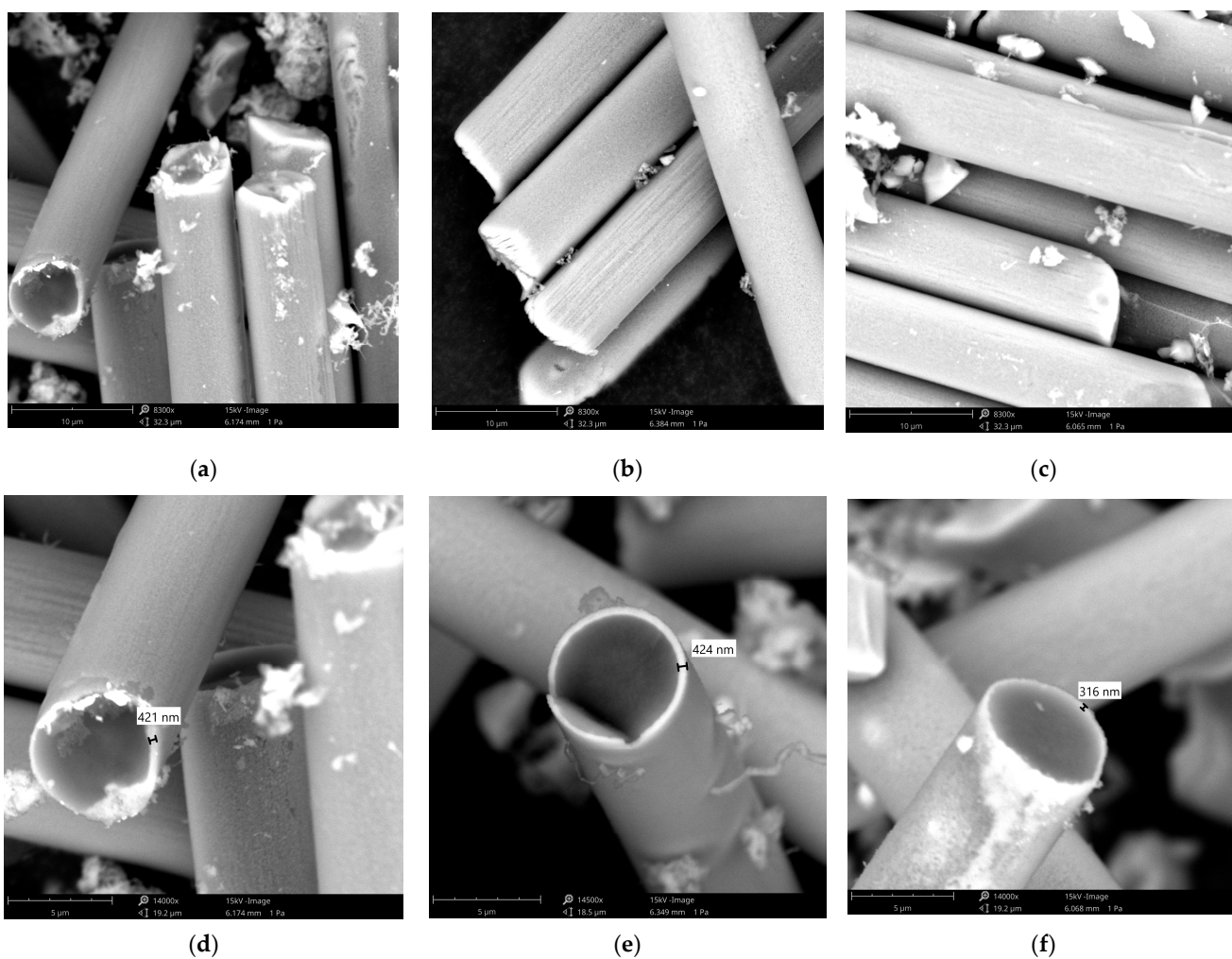


Figure 8. SEM images of rCFs treated at same rCF:Si ratio (1:0.25), same residence time (90 min) and different process temperatures: test 8 (a,d), test 7 (b,e) and test 3 (c,f).

Figure 9 shows the EDS analysis of the rCF core and coating and confirms the presence of Si and C from SiC on the rCF surface, as well as the presence of carbon in the core of the fibers: these results strengthen the XRD data concerning the nature of the ceramic coating.

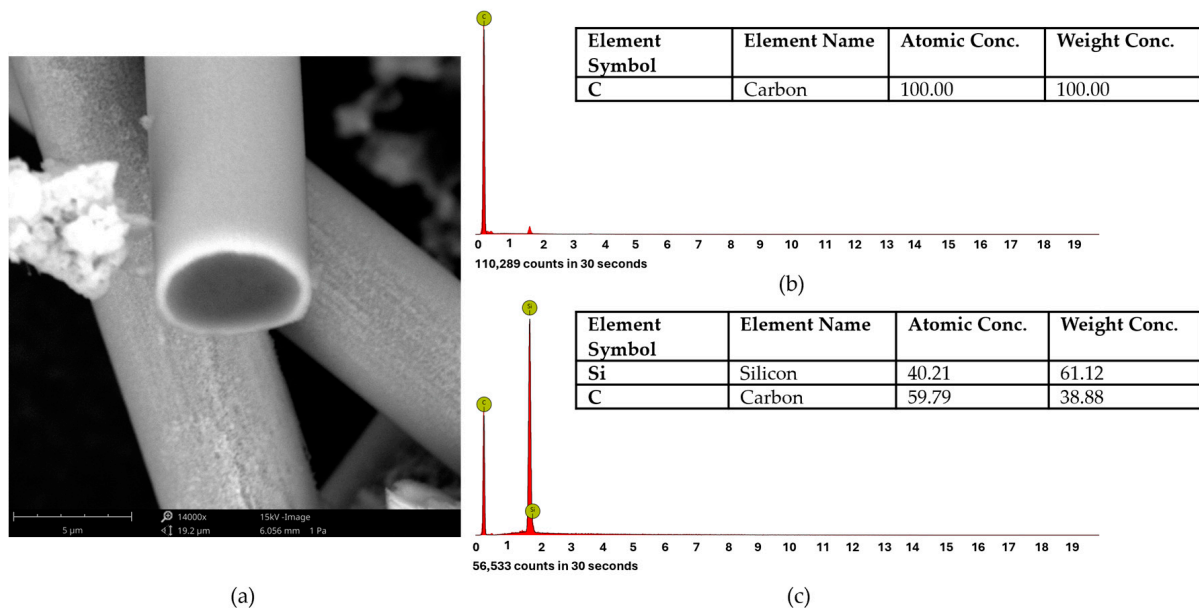


Figure 9. EDS analyses of rCFs treated in test 3 (a) on fiber core, point 1 (b) and on SiC coating, point 2 (c).

3.4. Oxidation Resistance of SiC-Coated rCFs

The oxidation resistance of the ceramic composites was assessed through a thermogravimetric analysis of the reaction products, as illustrated in Figure 10. The analysis was conducted from room temperature to 1000 °C in an airflow environment and compared to the analysis of the raw fibers.

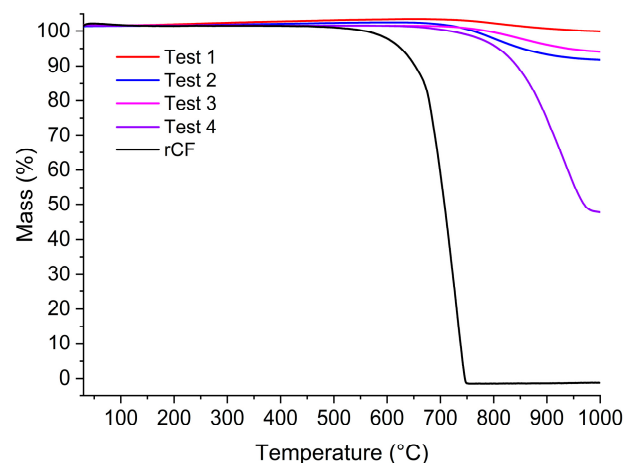


Figure 10. Thermogravimetric analysis of raw fibers and SiC-coated rCFs (tests 1, 2, 3, 4).

All ceramized fibers analyzed exhibit enhanced oxidation stability when compared to raw recycled carbon fibers, remaining stable up to 500 °C and completely decomposing at 750 °C. Tests 1 and 2, which have the highest silicon content ratio (1:1 and 1:0.5, respectively), show a slight increase in weight, probably due to the oxidation of unreacted silicon, prior to weight reduction due to the combustion of the carbon fibers. Conversely, test 4, which has the lowest silicon content, experiences the greatest weight loss of about 52%; this result is consistent with the lower fiber coverage indicated by SEM and XRD analyses. In all cases,

the fibers with the ceramic layer maintain oxidation stability at temperatures exceeding 750 °C. Notably, the coated carbon fibers from test 3 exhibit stability up to 795 °C, with a mass loss of around 5% occurring between 795 and 950 °C.

4. Discussion

Silicon carbide coatings are extensively utilized to improve the oxidation resistance and mechanical characteristics of carbon fibers; however, achieving this feature requires the establishment of a stable structure for the coating layer by creating interfaces between the carbon fiber and the SiC coating. Consequently, various critical factors can affect the stability and oxidation behavior of these composites, including the technique employed for SiC coating deposition, the microstructure and chemical composition of the fibers and the coating and its thickness.

This study employed a direct reaction with silicon to apply a SiC coating onto recycled carbon fiber. The formation of SiC occurs through the initial dissolution of carbon in molten silicon, which is succeeded by the heterogeneous nucleation, growth and aggregation of SiC particles on the carbon surface. Subsequently, the solid-state diffusion of silicon takes place as the thickness of the SiC layer surpasses several nanometers. A core-shell structure is formed, which can be observed in the SEM images of SiC-coated recycled carbon fibers (Figures 3, 6 and 8). The carbon fibers partially react with silicon, resulting in a SiC shell that encases a carbon core [30].

This approach is consistent with achieving a dense and uniform SiC coating that effectively inhibits oxygen diffusion. In fact, the SEM images of SiC-coated rCFs (Figures 2, 5 and 8) typically reveal a dense coating that is free of cracks.

It is crucial to recognize that the thermal recycling process has rendered the utilized carbon fibers (rCFs) free of sizing and functionalized with oxygen-containing functional groups [29,31,32]. These functional groups may improve the compatibility of the fibers and their adhesion to the SiC coating, thereby enhancing the overall material performance and rendering additional functionalization treatments, commonly used in other studies [33], unnecessary. The existing literature lacks findings regarding the SiC coating on recycled carbon fibers aimed at optimizing their oxidation behavior; rather, most studies concentrate on virgin carbon fibers or carbon fiber-reinforced composites.

The coating's thickness is crucial as it significantly influences the effectiveness of high-temperature resistance. An optimal thickness guarantees adequate protection while preserving the mechanical properties of carbon fibers. Although thicker coatings generally offer enhanced protection against oxidation, they can also lead to stress concentrations and potential defects if not applied uniformly [34].

The ideal thickness of SiC coatings may differ based on the application and the required characteristics. Research indicates that SiC-coated carbon fibers demonstrate considerable enhancements in oxidation resistance. Nevertheless, the presence of cracks within the matrix can facilitate oxygen diffusion into the composites, resulting in diminished oxidation resistance, particularly at intermediate temperatures ranging from 800 to 1100 °C [35].

SiC coatings with thicknesses in the range of 300–400 nm can greatly improve the oxidation resistance of carbon fibers [36]. For example, Huang et al. [37] demonstrated that carbon fibers coated with SiC, produced through spark plasma sintering, significantly enhanced oxidation resistance, raising the oxidation temperature by approximately 140 °C.

In this study, the thickness of SiC coatings was optimized by modifying the process parameters (molar ratio of rCF to silicon, reaction temperature and residence time). A distinct trend was noted, indicating that higher rCF:Si ratios corresponded to a decrease in coating thickness—equal to 630 nm, 404 nm and 316 nm for rCF:Si molar ratios of 1:1, 1:0.5 and 1:0.25, respectively. This observation implies that a higher silicon content (and lower rCF:Si

ratios) facilitates the deposition of thicker SiC coatings, likely due to the increased availability of silicon reactant during the process. In contrast, a lower Si content (and higher rCF:Si ratios) leads to a diminished silicon supply, resulting in thinner coatings.

The thickness of the SiC layer increases progressively with extended reaction times, rising from approximately 316 nm to 400 nm and ultimately reaching 689 nm after reaction durations of 90, 150 and 180 min, respectively. This trend is consistent with the existing literature, which indicates that SiC thickness increases with longer deposition periods. For instance, studies on SiC-coated fibers have shown that SiC thickness increases exponentially with longer deposition time, reaching approximately 1.5 μm after 4 h [38]. This exponential increase is attributed to the ongoing deposition of SiC over time, resulting in thicker coatings.

Moreover, it was noted that increasing the process temperature resulted in a reduction in SiC thickness. Specifically, at 1650 $^{\circ}\text{C}$, the carbon fiber coating measured 316 nm, which was thinner than the coatings of 421 nm and 424 nm recorded at 1450 $^{\circ}\text{C}$ and 1500 $^{\circ}\text{C}$, respectively. It is likely that the surface of SiC/C fibers at 1450 and 1500 $^{\circ}\text{C}$ are still surrounded by unreacted Si, which is responsible for increasing coating thickness.

According to a model for the siliconization of carbon, an initial reaction occurs between carbon and liquid silicon, resulting in the formation of a continuous SiC layer at the interface. The further growth of SiC is controlled by the diffusion of carbon atoms, in addition to silicon atoms, through the already formed SiC layer [39]. The newly formed coated rCFs nearly approximately maintain the dimensions of the original carbon fibers, which suggests that silicon has diffused from the exterior to the interior of the carbon fiber, resulting in the formation of SiC [30].

The SiC-coated recovered carbon fibers in our study are stable up to 795 $^{\circ}\text{C}$, particularly for the fibers of test 3, whose measured thickness (about 300 nm) is consistent with the literature findings. Additionally, it is worth noticing that the recovered carbon fibers have a lower initial oxidation stability compared to virgin fibers, and the SiC coating enhances the overall oxidation stability of the recovered carbon fibers by approximately 60%.

5. Conclusions

Recovered carbon fibers (rCFs) were successfully obtained from the polyphenylene sulfide/carbon fiber (PPS/CF) composite scrap materials generated through sheet lamination-based additive manufacturing. The resulting rCFs exhibited clean surfaces with diameters and lengths closely matching those of the virgin fibers. Post-processing yielded a heterogeneous length distribution ranging from 5 to 400 μm due to mechanical finishing treatments. The recovered fibers were used as a reactant in the synthesis of silicon carbide (SiC) via a Chemical Vapor Reaction (CVR) process. The reaction was conducted in a flowing argon atmosphere using elemental silicon as the precursor. Key synthesis parameters—including the molar ratio of rCF to silicon, reaction temperature and residence time—were systematically investigated. Optimal coating morphology and coverage were achieved at 1650 $^{\circ}\text{C}$ with an rCF:Si molar ratio of 1:0.25 (test 3). A clear trend was observed wherein the SiC layer thickness increased with prolonged residence time and with reduced processing temperatures.

A thermogravimetric analysis (TGA) of the SiC-coated fibers demonstrated significantly enhanced oxidative stability. While untreated rCF samples exhibited onset oxidation at approximately 500 $^{\circ}\text{C}$, the coated counterparts showed increased thermal resistance, with oxidation delayed to ~ 750 $^{\circ}\text{C}$. The most thermally stable coatings were associated with fibers processed under the conditions defined in test 3. Further optimization studies are ongoing, focusing on improving coating uniformity and minimizing the formation of secondary phases or unreacted by-products.

This work highlights a viable and sustainable method for valorizing carbon fiber waste through SiC surface functionalization. The integration of recycled rCFs into CVR-based SiC synthesis represents a strategic advancement in the development of oxidation-resistant materials for high-temperature or aggressive environments while contributing to cost reduction and circular economy objectives in advanced materials manufacturing.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

rCF	Recycled carbon fiber
CVR	Chemical vapor reaction
SiC	Silicon carbide
CFRC	Carbon fiber-reinforced composite
CVD	Chemical vapor deposition

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